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Topographical changes of ground surface affected by the shelterbelt along the Tarim Desert Highway

LI ShengYu[1†], LEI JiaQiang[1], XU XinWen[1], WANG HaiFeng[1,2], FAN JingLong[1,2], GU Feng[3], QIU YongZhi[3], XU Bo[3], GONG Qing[4] & ZHENG Wei[4]

[1] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China;
[2] Graduate University of the Chinese Academy of Sciences, Beijing 100049, China;
[3] Tarim Branch, PetroChina Company Limited, Korla 841000, China;
[4] Weather Station of Tazhong, Qiemo 841000, China

To study the effects of sand protection project on modern aeolian landform, the types, distribution, and intensity of topographical changes of the ground surface affected by the shelterbelt along the Tarim Desert Highway were determined by measuring the deflation and deposition of sand surface in the Tazhong area located in the hinterland of the Taklimakan Desert. The results showed that (1) the newly-formed landform in sand protection systems is dominated by aeolian deposition including the small-scale Nabkha Dunes, the medium-scale sheet-like sand deposition and the large-scale ridge-like sand deposition. To some degree, aeolian deflation landform can also be formed in the open space in the shelterbelt. Furthermore, it is difficult for aeolian deflation landform to develop in a large scale in the interdunes. However, aeolian deflation landform can be developed in a large-scale on the windward slope of secondary dunes in longitudinal complex sand ridges; (2) on the windward side of the sand protection systems, both the morphology and strike of dwarf mobile dunes in the interdunes are changed by the sand-obstructing forest belts and the ridge-like sand deposition around it. The windward slope of the ridge-like deposition around the sand-obstructing forest belt forms a stable ground surface. After being damaged by forward-moving dunes in a short period, the ground surface is recovered gradually; (3) on the leeward side of the sand protection systems, aeolian deflations are formed widely. Particularly, the deflation depression is formed in the interdunes. In addition, the dunes in the region with highly topographic relief are cut flat by aeolian deflations; thereafter its relief of topography is reduced. The above analysis indicates that shelterbelts have obvious effects on the windward wind-sand flux in terms of dissipating energy and intercepting sand. With the recovery of wind velocity on the leeward side of the sand protection systems, the wind-sand flux gradually tends to be unsaturated; therefore the sand surface deflation is formed.

aeolian landform, deflation and deposition of sand surface, shelterbelt, Tarim Desert Highway

There exists mutual acceleration and dynamic equilibrium between windblown sand activity and aeolian bed surface[1−3]. On the one hand, ground surface topography is mainly determined by winds. On the other hand, the ground surface can affect wind flow and windblown sand activity near the ground surface, and lead to the further topographical changes of its own. Many field investigations about the deflation and deposition on the ground surface have been conducted[4−10]. However, most works have been focused on sand disaster control[11−15] as well as the benefits of sand protection sys-

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†Corresponding author (email: lishy_hb@163.com)
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tems[16 − 18]. Few studies dealt with the topographic changes of ground surface caused by large-scale desert projects[8−10]. Particularly, highways are very common large-scale projects in deserts, and the long-term topographic changes of ground surface along the Tarim Desert Highway may lead to the changes of disaster-forming environments. Therefore, the studies about the topographic changes of ground surface caused by the sand protection systems are not only of significance in terms of the effects of human being projects on modern aeolian geomorphological process, but also of practical application in the context of the development and evolvement of sand disasters along the Tarim Desert Highway as well as the sustainability of highways.

1 Aeolian environmental backgrounds of the study area

The Tarim Desert Highway crosses the Taklimakan Desert in the Tarim Basin, northwest of China, from Luntai in the north fringe of the Tarim Basin to Minfeng in the south fringe. Its total length is 562 km, of which 446 km is located in mobile desert. It is the longest highway across deserts in the world (Figure 1). It was initially constructed in 1993 and completed in 1995. Particularly, about 50% of its mobile desert part is in the areas with the topography of highly complex longitudinal sand ridges. As a result, the landform along the Tarim Desert Highway is predominated by highly complex sand-ridges as well as the broad flat interdunes. A physical sand protection system has been constructed to protect the highway from the damages by the strong blown sand activities in the Taklimakan Desert[13]. Although this sand protection system can effectively decrease the damages, the rapid development of the blown sand disasters seriously affects the normal operation of the Tarim Desert Highway[14,15]. It has been shown that the biological sand protection system is probably the only essential method to control blown sand disasters. A lot of scientific experiments about the construction of shelterbelts have been conducted. Specifically, the key technical problems about the construction of artificial shelterbelts in the desert hinterland have been solved during the "Eighth Five-Year" and the "Ninth Five-Year". Particularly, the experimental and demonstrational project of biological sand-control along the roads of the Tazhong Desert Oil Field with the length of 30.8 km has been set up by irrigation with saline ground water. The project has shown obvious effects on sand prevention. Similarly, to ensure the long-term and safe operations of the Tarim Highway, the ecological project of shelter forests along the Tarim Desert Highway was initiated in 2003, based on the test researches that have been lasted over ten years. The project was accomplished in 2005. The shelterbelt covers an area of 3128 hm^2, with 436 km in length and 72—78 m in width. The shelterbelt has three layout patterns, that is, the four-belt pattern in the interdunes and small dunes, the two-belt pattern in the high-complex sand dunes or ridges, and the three-belt pattern in the transition areas between the high-complex sand ridges and the interdunes. The plant species are *Callignonum*, *Tamarix* and *Haloxylon ammodendron*, which were mixed cultivated among rows with a planting distance about 2 m and a row spacing about 2 m.

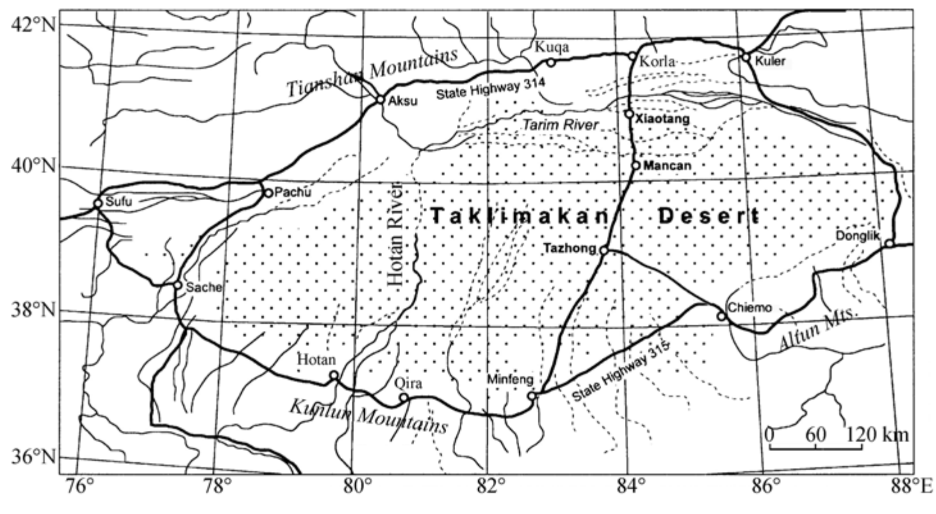

Figure 1 Map showing the location of the Tarim Desert Highway.

The shelter forest ecological project along the Tarim Desert Highway not only prevents the highway from the blown sand hazards, but also improves the eco-environment along the Tarim Highway.

The area studied here is located in the Tazhong Si area in the hinterland of the Taklimakan Desert, northwest of China. The sand-ridges, covered with secondary sand dune chains of 5—15 m in height, and running with a mean strike of 50°—60° north by east[19], are 30—70 m high. The interdunes, covered with some sand dune chains, barchan dunes and small sand ridges[14], are flat, with a width of 1—3 km. The ground surface is mainly composed of shifting sands dominated by fine sand and very fine sand with a mean grain diameter of 0.1—0.05 mm. In contrast, the sand on the interdunes is composed of fine gravel, most of them have a diameter of 0.5 mm, but some have a diameter greater than 2 mm[19]. Wind in this area is very strong and predominately frequent from March to September[20]. The annual average wind velocity is up to 2.5 $m \cdot s^{-1}$, with a maximal instantaneous wind speed of 20.0 $m \cdot s^{-1}$. The annual frequency of sand-driving winds, whose threshold velocity is 6.0 $m \cdot s^{-1}$ at the height of 10 m from the ground, is more than 500. The main direction of sand-driving winds is ENE, NE, NNE and E, among which the wind in the direction of ENE is the most frequent and the strongest.

2 Experiments and methods

In this paper, we studied the area of the shelterbelt along the roads of the Tazhong Desert Oil Field (Figure 2), where stand ages are 5—8 a; therefore the topographical changes of ground surface are obvious. The monitoring sections were set after the shelterbelt had been built up. The No.1 experimental field is located in the interdune flat ground, and the observation sections are selected according to the shelterbelt structure, including the sand-binding forest belt, sand-obstucting forest belt + sand-binding forest belt, sand-obstucting forest belt + sand-binding forest belt, reed sand-obstructing fence + sand-binding forest belt. The No.2 experimental field was set according to the geomorphologic positions, including 2 sand-obstructing belt + sand-binding belt in the interdune flat ground, sand-binding belt in the secondary dune area at the top of ridges, sand-obstructing belt + sand-binding belt in the secondary dune area of transitional zone between ridges and interdunes. The deflation and deposition of the sections are observed with many metal bars embedded in sand. The initial exposed height of the metal bar is H. The exposed height h is periodically measured every year, and the depth of each point is calculated by the formula of $D = H - h$ ($D > 0$ is deposition, $D < 0$ is deflation). The relative height E' of each point was surveyed with total-station instrument, then, the initial setting relative height was calculated by

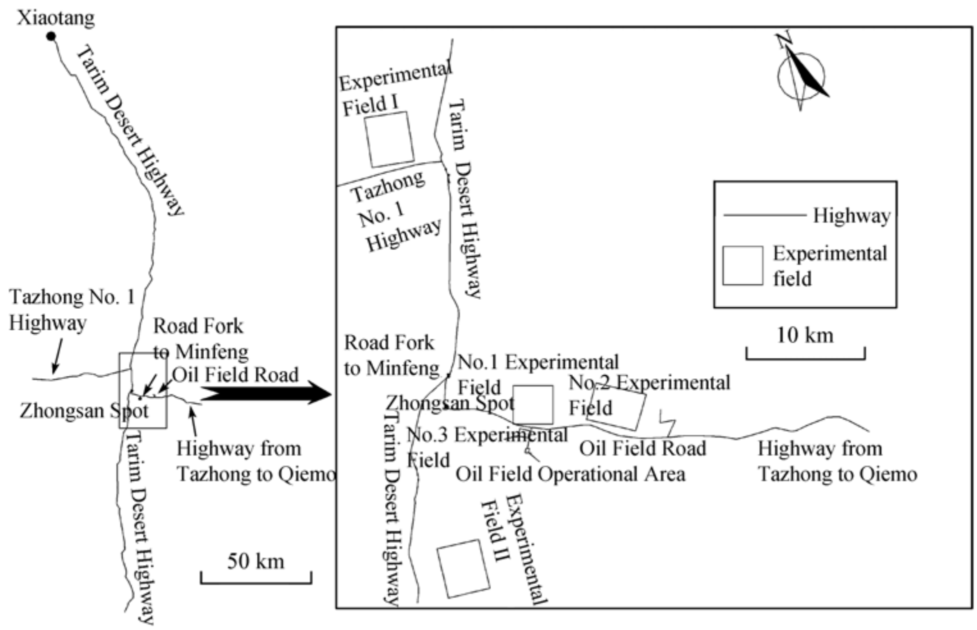

Figure 2 Map showing the position of experiment area and the distribution of test sites.

the formula of $E= E'-D$ in 2005 and 2006. The No.3 experimental field is located in the northeast of Tazhong Botanical Garden (planted in 2003). The sand deposition shape of the plant shrub was surveyed with total station instrument in 2007, and the corresponding 3-D contour chart was plotted with the software of Surfur8.0.

The windward edge of sand-obstructing forest belt is located close to the sand deposition body around the sand-obstructing fence in physical sand protection systems. Its effect on the movement and morphology of mobile dune is similar to that of physical sand protection systems, so the observation data of two experimental fields in 2004 are used. Experimental fields I and II lie in the interdune flat ground of No.1 Highway and the neighborhood of K364 milestone of the Tarim Desert Highway respectively.

The variations of wind profile at the section of mobile dunes are surveyed with the multi-point wind profile instrument at different geomorphologic positions. The weather data are observed at Tazhong weather station.

3 Results and discussion

3.1 Changes of aeolian landform in shelterbelts

3.1.1 Aeolian depositional micro-relief. (1) Plant nebkhas-like sand deposition. Nebkhas, which are the major exhibition form of wind break and sand fixation by vegetation, result from the deposition of sandy substance in and near shrub due to their barrier of wind-sand flux in arid, semiarid and semihumid desert areas[20−27]. In April, 2007, the research on the No.3 experimental field found that the bottom of *Haloxylon*, *Calligonum*, and *Tamarix* in the shelterbelt generally formed nebkhas, with similar shapes. A three-dimensional isoline map of the thickness of *Haloxylon* nebkhas sand deposition in the No.3 experimental field is shown in Figure 3. It is obvious that the shape of nebkhas is round, close to a semi-ellipsoid with symmetric shape (Figure 3(a), (b)). The closer to the bottom of *Haloxylon*, the thicker the sand deposition; the thinner on the contrary. The deposition has the maximum height of 0.18 m, with a volume of 0.346 m^3 and annual average mass of 0.0865 m^3. The vertical projection of sand deposition is almost elliptic, in a long-axis direction of NE→SW which is basically the local predominated wind direction, and a short-axis direction of NW→SE (Figure 3(a)) which is consistent with the conclusion drawn from the other research areas by scholars. The lengths of long and short axes are 1.6 m and 1.5 m, respectively, close to the coronal breadth of that plant in 1.60 m×1.52 m area (Figure 3(b)). However, the relationship between the range of sand deposition, the changes of wind field, and the height of plants cannot be explained by the shape of nebkhas due to the narrow row spacing of shelterbelts[21,24]. It is also found that the volume of nebkhas near the root of *Haloxylon* is the largest, i.e., 165.85±13.76 cm in average diameter, 15.02±4.09 cm in average maximum thickness, while that near the root of *Tamarix* is the second, 149.38± 15.98 cm in average diameter, 14.25±2.76 cm in average maximum thickness. The volume of nebkhas near the root of *Calligonum* is the smallest. In addition, the size of shrub sand deposition is closely related to the growth of plants as well as their coronal shape. Specifically, the branch of *Haloxylon* is dense whereas its underbranch height is small, while the branch of *Tamarix* is sparse but its underbranch height is relatively large. However, *Tamarix* is exceptional: its branch is dense, but its height is less than that of *Haloxylon* and *Calligonum* due to its slow growth.

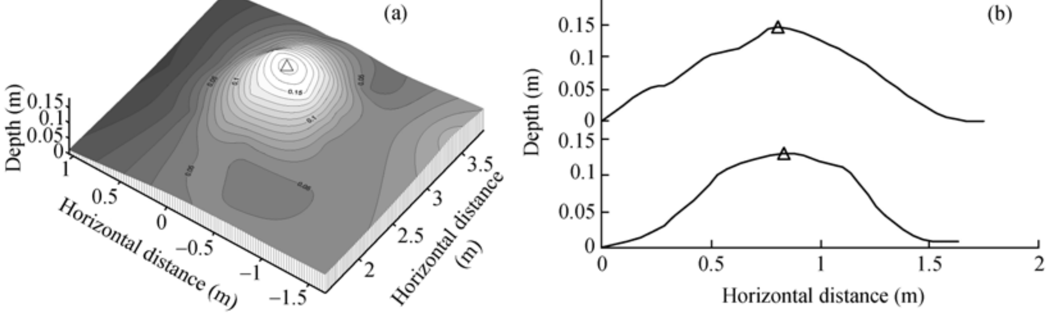

Figure 3 The 3-D contour chart (a) and cross-section graphs (b) of nebkhas around *Haloxylon* plant.

The surveys of sand-obstructing forest belt between the ridges in the No.2 experimental field showed that there are large sand cone around the majority of plants. Among them, those around *Haloxylon* are largest. This phenomenon may be related to the local available amount of sands. Particularly, wind-sand flux mostly moved along the main wind direction, so most sandy substance deposited inside the sand-obstructing forest belt, only a little suspended sand can arrive to the interior of the sand-binding forest belt. As a result, the available sand amount in the sand-obstructing forest belt is higher than that in the sand-binding forest belt. The wind velocity at the ground surface can be significantly weakened, by the shelterbelt, in which most of sandy substance is deposited and litter is also preserved. Subsequently, the structure of sand depositional layer is more stable, leading to the sustained development of nebkhas. It indicates that the well-preserved litter can facilitate the development of nebkhas. The results of this survey confirmed the conclusions drawn by other scholars that all of the wind regime, the sand availability and the types of vegetation are important factors that influenced the forming and shaping of nebkhas[25,26].

According to the classification of combination patterns, in our study area, the nebkhas inside the sand-binding forest belt belong to the individual mode, while those inside the sand-obstructing forest belt are the composite mode, in which the neighboring nebkhas are connected with each other. Because the distance between trees and rows of the forest belt is 1 m×1 m in majority, the neighboring nebkhas in the sand-binding forest belt gradually link with each other with their development, to form the composite nebkhas, which increases the height of the ground surface of woodlands.

(2) Ridge-like sand deposition in the edge of shelterbelts. The No.1 study area is located at the windward side of the highway. Its biological sand protection system, established in 1999, includes a sand-obstructing forest belt and a sand-binding forest belt. The survey in October, 2006 indicated that ridge-like sand deposition, of which the slip face is deflected towards the windward slope affected by southwestern wind, began to develop near the sand-obstructing forest belt. From Figure 4 we can see that the transection of ridge-like sand deposition is similar to that of barchan dunes with a gentle windward slope and steep slip face (25°—29°). The windward surface of sand deposition was concave with a slope gradient increase from the bottom to the top, i.e., 3.36° at the bottom, 14.81° in the middle and 20.05° on the top. The height of the sand deposition lay in the leeward edge of the sand-obstructing forest belt. Meanwhile, the sand deposition on the edge of the sand-binding forest belt was also ridge-like, whose transection was similar to that of barchan dunes as well. But its height was smaller. Moreover, the top of sand deposition was located inside the shelterbelt, which is consistent with the results reported by Liu et al.[28]. It is because the wind field of ground surface has been attenuated by the shelterbelt, the sand deposition was first formed in the windward edge of the sand-obstucting forest belt and the height of sand deposition increased with sand accumulation. Moreover, the leeward part slowly migrated towards the interior of the shelterbelt while the windward part rapidly extended until forming dune-like sediment with a long gentle windward slope and a short steep leeward slope. As shown in Figure 4, because the sand-obstructing forest belts were formed at the sand deposition with original meshed nylon fence and reed fence, the size of ridge-like sand deposition was very large, as large as 3.87 m in height and 38 m in width, and in particular, the width of the windward part (31 m) is larger than that of the leeward part (7 m).

Studies found that there was some sediment in the leeward part of the shelterbelt along the highway, but its

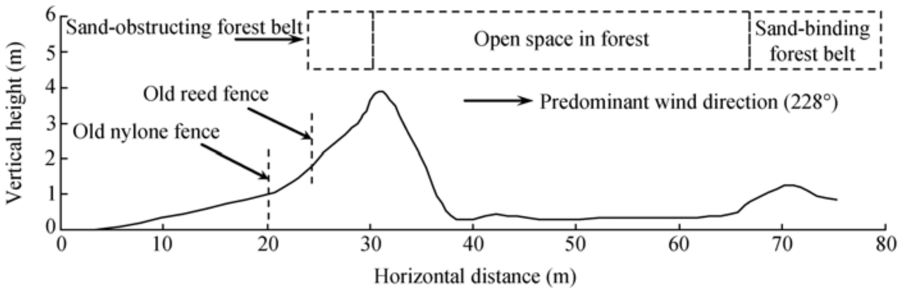

Figure 4 Cross-section chart of sand deposition in the shelterbelt on flat sandy ground in interdune corridor.

amount was less because of the weak windblown sand activity of the local inverse wind direction. In contrast, on sand ridges and the transition regions between the ridges and the interdune areas with high topographical relief, little sandy substance in wind-sand flux was deposited in the windward edge of the shelterbelt whereas a lot of it was deposited in the inner parts of shelterbelts. These observations indicate that landforms may have significant effects on sand deposition. However, the lack of physical sand protection systems may also be responsible for the observed difference in the sand deposition.

(3) Sheet-like sand deposition inside the shelterbelt. Figure 5 shows the longitudinal profile of three sand-obstructing forest belts and sand-binding forest belts that were constructed in 1999 in No.1 experimental field. The first sand-obstructing forest belt, constructed onto the sand deposition of two old fences, can hold up plenty of sandy substance. A high ridge-like sand deposition with a maximum depth of 3.5 m was formed, while the height of sand depositions in other two sand-obstructing forest belts and sand-binding forest belts were relatively small, the maximum height was 1.04 m, 0.99 m, 0.67 m, respectively. However, the height of sand depositions inside the shelterbelt was small: the maximum height of sand depositions between the second and third sand-obstructing forest belts, and between the third sand-obstructing forest belts and the sand-binding forest belts, is only 0.46 m and 0.54 m, respectively. In addition, all sediments were deposited in the form of flaky layers. The wind velocity was rapidly reduced in the windward edge of shelterbelt. Most sands deposited on the way, only a little migrated into the inner parts of shelterbelts with the airflow and then deposited there. Most of sediments deposited in shelterbelts are suspended load with fine particle size as well as some saltation load. Particularly, fine particles deposited slowly. As a result, the height of depositions affected by shrub varies little, and they formed flaky layers on the ground surface.

In No. 2 experimental field, the observed transaction covers a secondary dune on top of sand ridges in the windward side of the shelterbelt. The sand-binding belt of reed checkerboard was constructed onto the windward slope of the dune, while the sand-binding forest belts were constructed on both the dune summit and the leeward slope in 2001. The results of survey in 2005 are shown in Figure 6. On the leeward slope of the dune, the amount of deposited sand on the upper part of the slope was largest, compared with that in the middle and the lower part of the slope where the spatial distribution of sand depositions is more uniform. It is obvious that, as

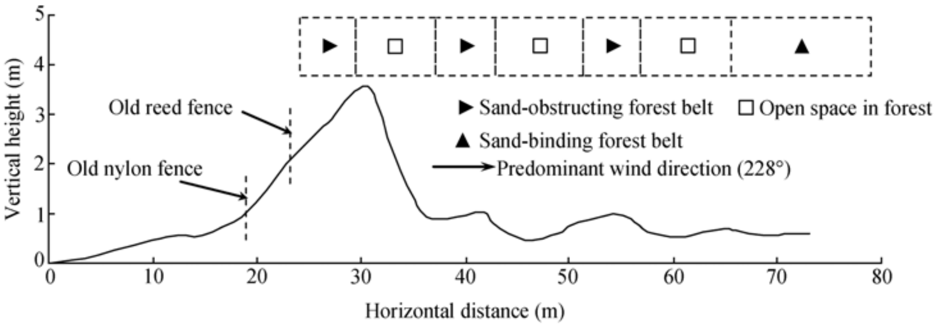

Figure 5 Cross-section chart of sand deposition in the shelterbelt consisting of three columns of sand-obstructing belts on sandy flat in interdune corridor.

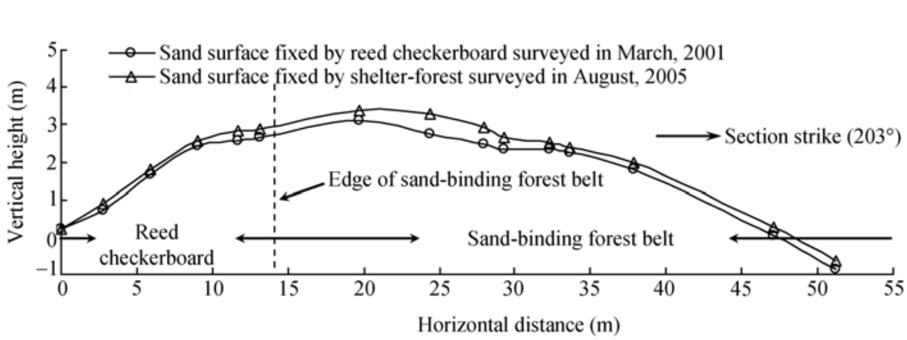

Figure 6 Cross-section chart of sand deposition in the shelterbelt on a secondary dune on top of complex longitudinal sand-ridges.

influenced by dune morphology, wind-sand flux may form eddy flow on the leeward slope of the dune. As a result, the majority of sand particles in airflows would deposit on the upper part of the slope, while, in flat inter-dune areas, most sand particles deposit on the edge of the shelterbelt.

3.1.2 Deflation micro-relief. (1) Blowout in open space in the shelterbelt. In the sand protection systems, a certain open space of 10—20 m in width has been left as the sand deposition belt between sand-obstructing forest belts and sand-binding forest belts, and between sand-obstructing forest belts.

The shelterbelt in the interdune area in the No.2 experimental field contains two sand-obstructing belts and one sand-binding forest belt that were cultivated in 2001. After the shelterbelt being settled, blowouts developed gradually between the second sand-obstructing forest belt and sand-binding forest belt with the depth of wind erosion of 0.62 m as measured in 2005 (Figure 7(a)). That can be explained as follows: passing airflow is greatly attenuated by the sand-obstructing belt. As a result, the majority of sand particles in wind-sand flux deposit here. Meanwhile, wind speeds up gradually on the downwind side of this area and wind-sand flux tends to be unsaturated and the relative capability of sand holding is increased, thus causing wind erosion in open space in the shelterbelt. With the increase in the size of sedimentary range in the leeward side of sand-obstructing forest belt, the position of blowouts moves gradually towards the leeward side and the previous blowouts were finally buried by sediments. Owing to burial by the sand deposition forward migration as well as the ground surface stabilization by sand-binding forest belt, blowouts could not develop extensively and were gradually buried by sediments.

In transition regions between ridges and interdune areas of the No.2 experimental field, the shelterbelt was covered by a secondary dune, and deflation pits occurred in open space in shelterbelts on the windward slope of the dunes. The results surveyed in 2006 (Figure 7(b)) showed that the depth of wind erosion had reached 0.25—0.29 m. The investigation in the neighboring zones found the depth of blowout in shelterbelts in the middle of some dunes could even reach 1.2 m, leading to the vast exposure of plant roots on the edge of shelterbelt. The intensive development of blowouts in the windward slopes of dunes is related to acceleration effects of dune morphology on upward wind flow, so the recovery of wind speed on the leeward part of sand-obstructing forest belts was faster than that on flat grounds. With the gradual development of blowouts in open space in forest belts on the windward slopes of

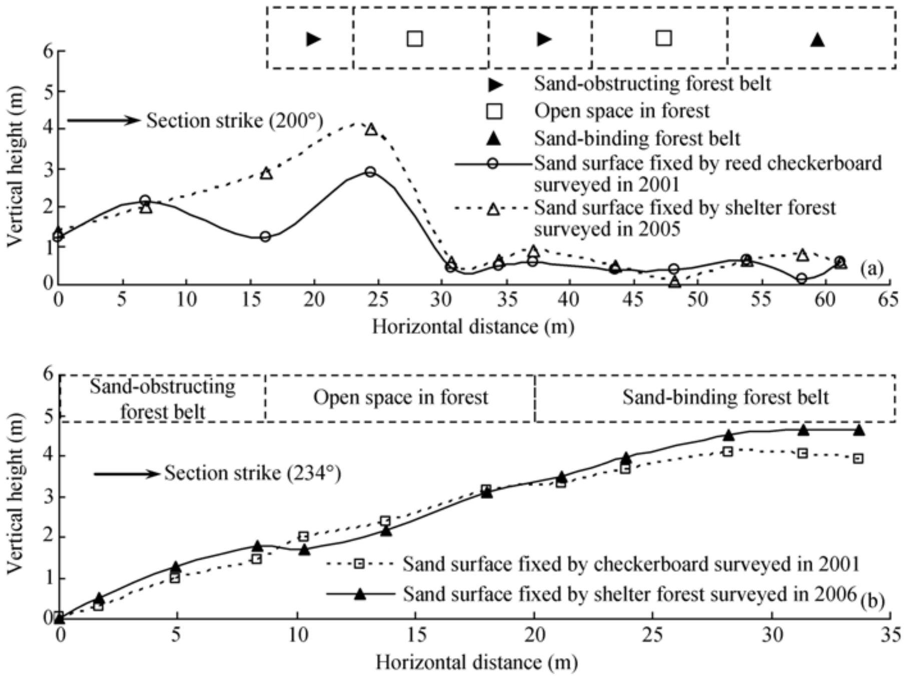

Figure 7 Charts showing wind erosion in open spaces in shelterbelts planted in sandy flat in interdune corridor (a) and on windward slope of a secondary dune on the transverse area between complex longitudinal sand-ridges and interdune (b).

dunes, the area can be stabilized, which is limited by the space of inter-forest, and the depth of blowout finally reached dynamic equilibrium.

(2) Wind erosion groove between plants. Micro-reliefs with shallow band-like grooves are usually formed on the top of ridge-like dunes on the edge of windward sand-obstructing forest belt, along with the space between plants. Generally, the micro-reliefs, called wind erosion grooves, are perpendicular to forest belts and with an orientation along the predominated wind direction. They show a comb-like morphology combined with forest belts, which relates to wind erosion among plants. Forest belts are high and vertical barriers with an inhomogeneous extent of porosity. The branches in canopy are dense with a low porosity, while the branches under canopy are sparse with a high porosity. Consequently, airflow can pass through the lower parts of plants easily. They are the major pathway as airflow passes the forest belts, and the wind speed increases here because of the narrow space, which is called narrow tube effect. Moreover, the edges of forest belts are located at the middle and upper parts of windward slope of ridge-like dunes because the summits of ridge-like dunes are in the interior of the forest belts. Wind speed can also be increased by the block of landform. So wind erosion groove among the plants can develop widely over the middle and upper parts as well as on the top of ridge-like dune.

The size of wind erosion groove is usually small, with a depth under 30 cm and a length of 100 cm. It is related to the space between plants. Specifically, it was found that the width, depth and length of wind erosion grooves exhibit a positive correlation with the space between plants (n = 40). The correlation coefficient is 0.897, 0.6003, and 0.2936, respectively. Furthermore, the width, depth and length of wind erosion grooves also show a positive correlation with each other. Specifically, if the space of plants increased because of the death of plants or man-made destruction, wind erosion grooves would also develop into a large size, and could even erode the dunes into a flat and smooth sand surface. Consequently, wind-sand flux can break through the sand protection systems via this gap in sand-obstucting forest belt and the overall protective benefit of the shelterbelt is reduced (Figure 8). Therefore, these gaps in forest belts have to be found and maintained in time in the post maintenance and management of the shelterbelt.

3.2 Changes of aeolian landform in the windward neighborhoods of shelterbelts

(1) Deformation of forward-migrating sand dunes A sand-obstructing forest belt together with associated ridge-like dunes is actually a combination of sand barriers. According to the morphological changes of the moving sand dunes at the windward side of the sand-obstructing fence in experimental fields I and II reported by Li et al.[29], dunes were not affected by forest belts when the distance between dunes and sand-obstructing forest belt is greater than 15H (H is the sum of the

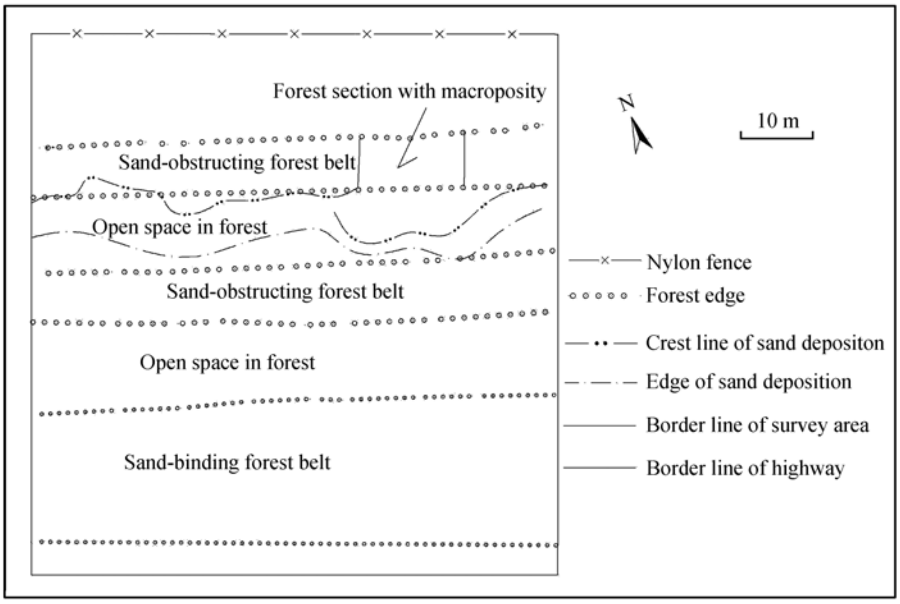

Figure 8 Graph showing the influence of a high plant-morality zone within sand-obstructing forest belt in interdune corridor on the movement of its surroundings sediment.

height of both the sand-obstructing forest belt and the ridge-like dune). However, when the distance is between $10H$ and $15H$, with the migration of dunes, their sizes including the height, width, the windward slope gradient and the volume of the dunes tend to increase, along with the concentrated distribution of sandy substance in dunes (both the length and bottom area of dunes decrease). When the distance is less than $10H$, the spatial distribution of sandy substance becomes disperse, with the increase in the length and bottom area of dunes, even though the size of dunes increases. Particularly, when the dunes and sand-obstructing forest belt are in contact, the height of dunes gradually decreases until it has the same height as the ridge-like deposition, as limited by the height of both forest belts and the ridge-like sand deposition. When the sand deposition by fences is little, a majority of sand are hold by sand-obstructing forest belts. However, when the amount of sediment on the windward side of sand-obstructing forest belts have been above its maximum, most sandy substances are carried by wind-sand flux to the inner parts of the sand protection systems and deposit in the sediment belt at the leeward side of sand-obstructing forest belts, or migrate downward further. Particularly, when the direction of main wind or the resultant sand-driving wind is approximately perpendicular to the sand-obstructing forest belt (the included angle is greater than 70°), there is little change in strikes of dunes because of the attenuation of wind speed at the ground surface by sand-obstructing forest belts. When their included angle is between 45° and 70°, with the approaching of dunes to sand-obstructing forest belts, the strikes of dunes gradually deflect, perpendicular to the sand-obstructing forest belts, when their included angle is smaller than 45°, the strikes of dunces are finally parallel to that of sand-obstructing forest belts.

(2) Deformation of sand deposition on the edge of forest shelterbelts. The sand-obstructing forest belts in the outermost parts of the shelterbelt along the Tarim Desert Highway were mostly settled onto the sediment of previous sand-obstructing fences. As a result, the sandy substance held by fences is accumulated onto the previous sediment, forming a ridge-like sand deposition with a large volume. Surveys in the No.1 experimental field found that the transection of sand-obstructing forest belts was essentially the same as that of barchan dunes with a concave windward slope. The base and upper part of windward slope were gentle with an angle between 2°—6° and 9°—14°, respectively, while the middle part was steep, whose angle is about 9°—22°. In contrast, the leeward slope is much steeper with a slip face in the maximal rest angle of sandy substance (Figure 9). During the windy seasons, the obvious change in the transection of sand deposition is the increase at the height of sand deposition as well as the downwind migration of both crest line and slip-face. However, the windward side of dunes is very stable. It can be inferred that the windward slope of ridge-like dunes has already reached the balance between erosion and deposition, in which wind-sand flux rises and accelerates at windward slope and forms non-accumulation transportation, and sandy substance deposit on the slip-face and the top of windward slope. Surveys also found that the windward slope of ridge-like dunes could be overlapped by forward-migration dunes and its morphology also changes. But under the long-term effects of wind-sand flux, dunes were gradually decomposed into the wind-sand flux which migrates towards slip-face and deposited there, and the slope surface tended to be stable finally. However, this stabilization is only temporary; the morphology of slope surface would gradually change and finally adapt to the new environments when sand-obstructing forest belts grow higher.

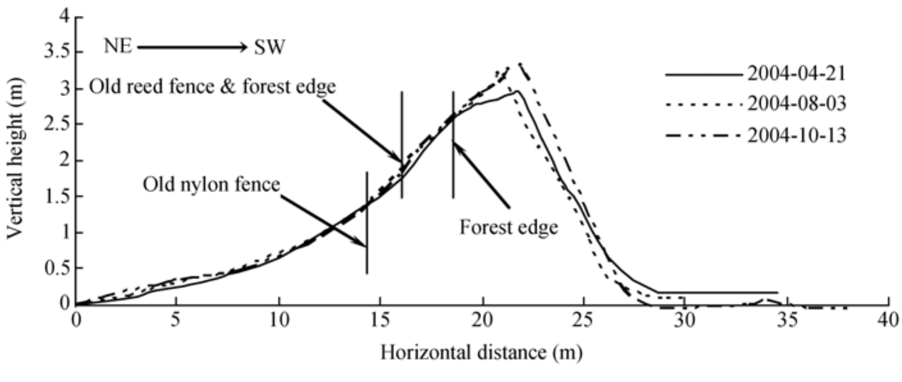

Figure 9 Chart showing dynamics of the transverse section of the sand-obstructing forest belt in interdune corridor.

When barchan dunes move forwards and gradually approach the ridge-like dunes on the edge of shelterbelts, its prozones would overlap on the windward slopes of ridge-like dunes. The windward slopes erode gradually and result in the formation of blowouts, even the exposure of plant root systems thereafter the fall of pants. It is because most sand grains were unloaded after the acceleration and rising up of airflows across the windward slopes as well as the deceleration of airflows across the slip-face, and in particular, with the speeding up of airflows in the prozones of dunes, wind-sand flux can be extremely unsaturated (Figure 10) and leads to the erosion in the prozones of dunes. However, with the forward migration of dunes, dunes would be merged with ridge-like dunes and bury the wind erosion pits.

3.3 Changes of aeolian landform in the leeward neighborhoods of the shelterbelt

(1) Interdune areas. Figure 11 shows schematically the sand protection systems along the highway in interdune in the No. 2 experimental field. It includes a former meshed nylon fence, two sand-obstructing forest belts (6—7 m wide) and sand-binding forest belt (20 m wide) at its windward side, a sand-binding forest belt (18 m wide) and a former sand-binding forest belt of reed checkerboard (36 m wide) at the leeward side. The total width of the sand protection systems is 142 m, in which the width of shelterbelt is 90 m including the open space in shelterbelt, the road surface and the road shoulders. In April 2004, in order to observe the transection, the metal bars were embedded in the reed checkerboards at the leeward side of shelterbelt and shifting sand land. These bars are perpendicular to the shelterbelt and the space interval of bars is 2 m. The transections were measured four times in the windy season.

The reed checkerboard is located outside the sand-binding forest belt, mostly buried by sand with approximately only 2—5 cm above the ground surface. In the windy season, the morphology of the ground surface changed constantly, however, in the survey area, there are five deflation areas and five deposition areas whose locations are relatively fixed. The depth of wind erosion of these deflation areas is generally 1—4 cm with a maximum of 6.5 cm, and the thickness of these

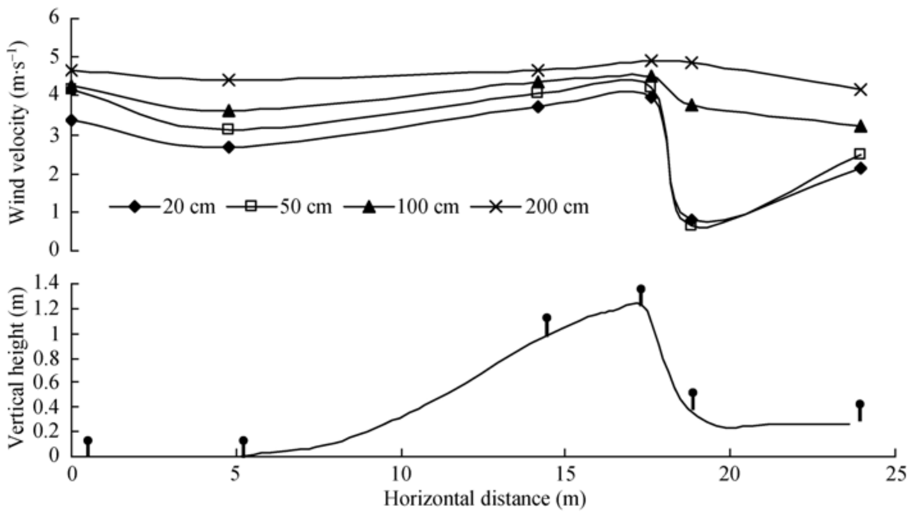

Figure 10 Graph showing wind velocity changes near the ground surface of a dwarf barchan dune.

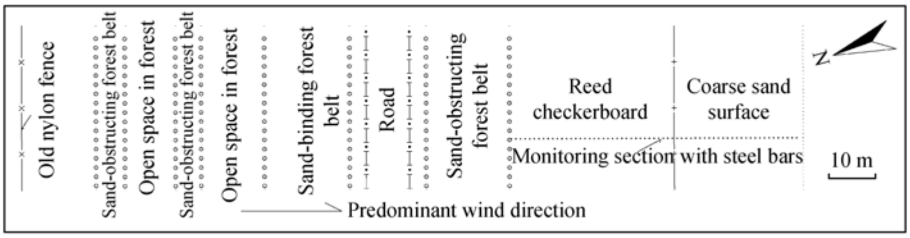

Figure 11 Diagram showing the structure of sand-control systems in interdune corridor and the location of observation transverse section.

sand depositions ranges from 0 to 4 cm, with a maximum of 7.3 cm. The results of these four measurements indicate that the amount of sand deposition in reed checkerboards keeps almost a constant, while the volume of erosion varied greatly. However, at the end of windy season (surveyed on October 7), checkerboards were in a state of net deflation (Figure 12, Table 1).

The shifting sand land outside the reed checkerboards is smooth and composed of coarse sand particles. In the windy season, there are four deflation areas and five deposition areas whose locations are stable in the survey area. The thickness of sand deposition on the ground surface was generally small and decreased with time while the depth as well as the range of wind erosion areas was increased with time (Figure 12). Particularly, at the end of the windy season, the ground surface was either eroded or kept the balance between erosion and deposition, with the maximum depth of wind erosion of 4.2 cm. The total amount of sand deposition decreased gradually with time, whereas the volume of erosion increased (Table 1). The shifting sand land was all in a state of net deflation in all measurements except that on May 2.

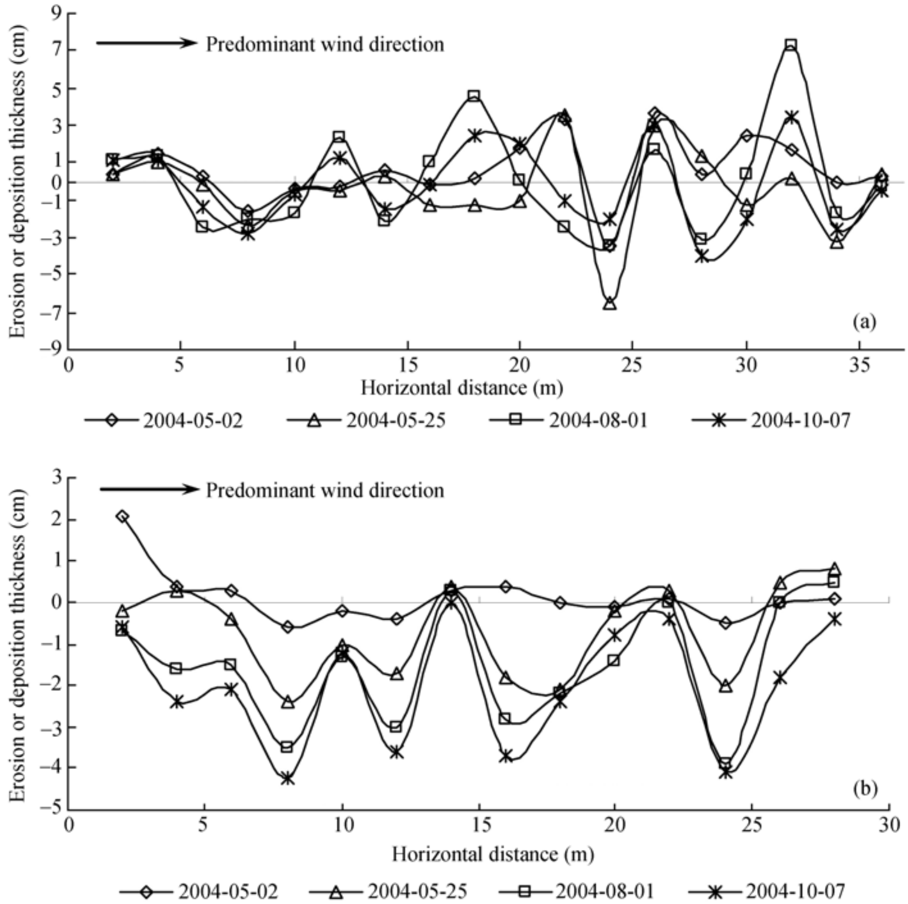

Figure 12 Chart showing distribution and dynamic changes of deflation and deposition in the leeward of shelterbelts in interdune corridor.

Table 1 Dynamics of the amount of the deflation and deposition ($m^3 \cdot m^{-1}$) on the flat ground in the leeward side of shelterbelts in interdune corridor

Position	Amount of deflation or deposition	2004-05-02	2004-05-25	2004-08-01	2004-10-07
Sand surface fixed by reed checkerboard barrier (36 m long)	net changes	0.217	–0.156	0.024	–0.065
	deflation	–0.041	–0.42	–0.245	–0.318
	deposition	0.258	0.264	0.269	0.253
Flat ground covered with coarse sand in the leeward side of the above (28 m long)	net changes	0.04	–0.194	–0.43	–0.555
	deflation	–0.028	–0.198	–0.425	–0.544
	deposition	0.068	0.004	0.005	–

Negative data denote the deflation, while positive data denote the deposition.

It can be concluded that the majority of sand particles in the wind-sand flux deposit in the shelterbelt, but in the leeward side of the shelterbelt the sand content of wind-sand flux is very low. With the recovery of the wind speeds in this area, wind-sand flux tends to be extremely unsaturated and leads to wind erosion on the ground surface. Based on the theoretical analysis, we can infer that the ground surface on the leeward side gradually turns into a state of balance between deflation and deposition from deflation as far from the shelterbelt. During the middle and later of windy season, the ground surface over a range of 64 m at the leeward side of the shelterbelt is in a state of deflation. Therefore the range of deflation on the leeward side of the shelterbelt should be larger than 64 m.

(2) Sand-ridge areas. On the top of ridge in the No.2 experimental field, the transection of the highway is in trench style. Figure 13 shows schematically the transection of the shelterbelt. Before the construction of shelterbelt (in 2001), the small secondary dunes outside the shelterbelt on the leeward side of the highway were convex. However, after five years of the construction of shelterbelts, the dune has been severely eroded and developed into a smooth and slightly concave surface with the maximum erosion depth of 1.5 m (Figure 14). It indicated that on the top of sand ridge the majority of sand particles in wind-sand flux have been held by shelterbelts and some sandy substance has been deposited in highway-trench with the depth of 5 m. Airflows are gradually accelerated across the windward slope of highway-trench and tend to be extremely unsaturated when they reached the outside of shelterbelts. It leads to severe erosion of the ground surface. Consequently, the topography of ground surface tends to be gentle with smaller relief.

4 Conclusions

The construction of shelterbelts along the Tarim Desert Highway has greatly changed the windblown sand activitys near the ground surface and led to deflation and deposition, which changed the morphology of the ground surface. The form and degree of this kind of change vary with their positions in shelterbelts: (1) In the inner parts of sand protection systems, deposition was dominated and led to the formation of nebkhas in a small scale, sheet-like sand deposition in a middle scale and ridge-like sand deposition in a large scale. There were also some deflations developed in the open space in shelterbelts, but it was difficult for them to develop on

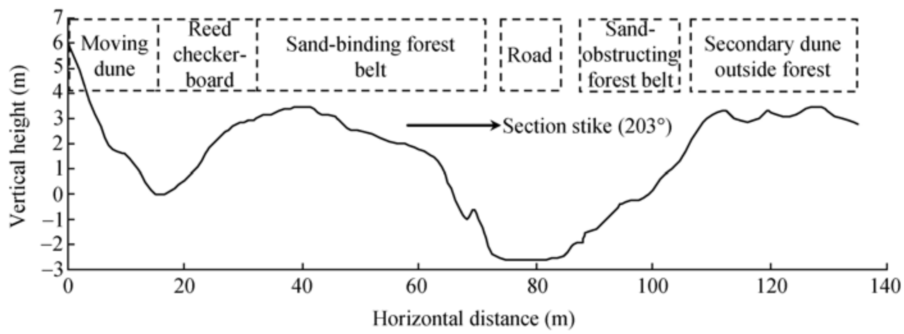

Figure 13 Chart showing trenc-shaped road transverse section on the top of complex longitudinal sand ridge and the location of a little sand dune in the leeward side of the shelterbelt.

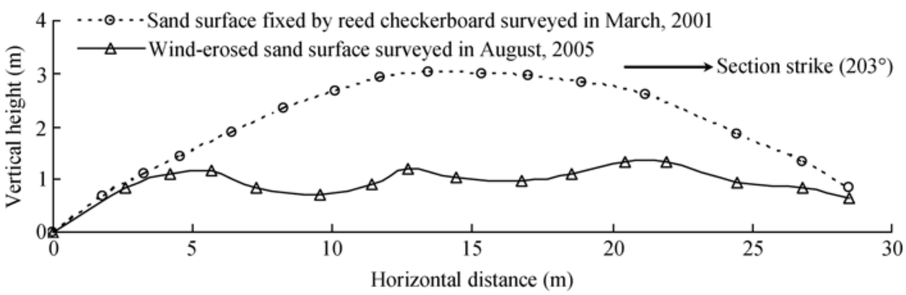

Figure 14 Chart showing changes of transverse section of the sand dune in the leeward side of the shelterbelt on top of sand ridges.

a large scale in interdune areas, but easy on the windward slopes of the secondary dunes on sand-ridges. (2) At the shifting sand surface on the windward side of sand protection systems, both the morphology and strike of low mobile dunes in interdune areas were changed by sand-obstructing forest belts and ridge-like dunes in their movement process; stable sediment slope would be formed on the windward side of ridge-like dunes around the sand-obstructing forest belts which can be deformed by the forward-migrating dunes in a short time and then gradually recovered. (3) A large range of deflation could develop in the shifting sand surface on the leeward side of sand protection systems, and blowouts can be developed in interdune areas. Dunes on sand-ridges can be razed and decreased the topographic relief of the ground surface. Therefore, the shelterbelt has a significant influence of dissipating energy and intercepting sand on wind-sand flux. Wind-sand flux tends to be gradually unsaturated with wind speeding up far from the leeward side of the shelterbelt, and leads to deflation on the sand surface.

With the influences of the shelterbelt along the Tarim Desert Highway, topographic changes of ground surface affect not only the local aeolian environments but also the sustainable and stable development of the shelter belt. There are also some problems: (1) the burial by sand deposition affects the normal operation of irrigation systems and increases the cost of maintenance. The growth and development of plants in the shelterbelt are also influenced by deposition and deflation on the ground surface; and (2) the original transection layout of the highway has been changed by a long-term deposition in the shelterbelt.. Trench-style transections of the highway are formed which facilitates the sand deposition on the road surface, affecting traffic. But there are also some advantages concerning sand deposition, for example, sand deposition layers can reduce the evaporation loss of soil moisture, increase the content of absorbable moisture in soil for plants, and make it difficult for salt crust layer to form on the ground surface in the shelterbelt, thereafter decrease salt disasters of plants by sudden rain.

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1 Ma S W, Ma Y M, Yao H L, et al. Study of Desert (in Chinese). Huhhot: Inner Mongolian Press, 1998. 17—18

2 Skidmore E L. Soil erosion by wind: An overview. In: El-Baz F, Hassan M H A. eds. Physics of desertification. Dordrecht: Martinus Nijhoff Publishers, 1986. 261—273

3 Zhu Z D, Zhao X L, Ling Y Q, et al. The Engineering of Sand Control (in Chinese). Beijing: China Environmental Science Press, 1998. 26—36

4 Bagnold R A. The Physics of Blown Sand and Desert Dunes (in Chinese, translated by Qian N). Beijing: Science Press, 1959. 172—218

5 Zhu Z D, Chen Y P, Wu Z. Study on the Geomorphology of Wind-drift Sand in the Taklimakan Desert (in Chinese). Beijing: Science Press, 198l. 27—80

6 Wang X M, Dong Z B, Qu J J, et al. Dynamic processes of a simple linear dune——A study in the Taklimakan Sand Sea, China. Geomorphology, 2003, 52: 233—241

7 Dong Z B, Wang X M, Chen G T. Monitoring sand dune advance in the Taklimakan Desert. Geomorphology, 2000, 35: 219—231

8 Zhen J G. Changes of surface feature of the stabilized mobile dunes at Shapotou southeast edge of Tengger Desert (in Chinese). J Des Res, 1987, 1: 10—17

9 Hang S L. The effect of windbreak and dune fixation forest on morphology and structure of dunes. Inner Mong Forest Sci Technol, 1998, 1: 42—44

10 Huang Q, Lei J Q. Sand-obstructing effect on the upright sand barriers in the different morphological sections along the Tarim Desert Highway. Arid Land Geog, 2000, 3: 227—232

11 Dong Z B, Chen G T, Han Z W, et al. Blown-sand disasters of the Tarim Desert Petroleum Highway (in Chinese). Environ Sci, 1997, 1: 4—9

12 Wang X Q, Lei J Q, Huang Q. Study on spatial distribution of wind-sand hazard along the Tarim Desert Highway, China (in Chinese). J Des Res, 1999, 4: 438—442

13 Tarim Petroleum Exploration and Development Headquarters, China National Petroleum Corporation. Tarim Desert Petroleum Highway (in Chinese). Beijing: Petroleum Industry Press, 1996. 535—549, 612—616

14 Lei J Q, Wang X Q, Wang D. The formation of the blown sand disaster along the Tarim Desert Highway, Xinjiang, China (in Chinese). Arid Zone Res, 2003, 1: 1—6

15 Li S Y, Wang D, Lei J Q. Spatial distribution of sand drift disasters on road surface in the hinterland of the Taklimakan Desert (in Chinese). Arid Land Geogr, 2005, 28: 93—97

16 Han Z W, Chen W N, Chen G T, et al. The protective efficiency of the drifting sand devil controlling systems along the test section of the Tarim Desert Highway (in Chinese). J Des Res, 1993, 4: 44—51

17 Xu X W, Hu Y K, Pan B R. Analysis on protection effect of various measures of combating drifting sand along the Tarim Desert Highway (in Chinese). Arid Zone Res, 1998, 1: 21—26

18 Wang X M, Chen G T, Han Z W. The benefit of the protection system along the desert highway in the Tarim Basin (in Chinese). J Des Res,

1999, 2: 120－127
19 Wang X M, Dong Z B, Chen G T. Characteristics of blown sand environment in the middle of the Taklimakan Desert (in Chinese). J Des Res, 2001, 1: 56－61
20 Li H P, Chen G T, Xue D Q. Wind field over complex dune-chains and the dynamic features of the dunes overlaying on the dune-chains in the hinterland of the Taklimkan Desert (in Chinese). Arid Land Geogr, 2001, 1: 80－85
21 Wu S L, Li Z Z, Hai Y. Experimental study on the airflow patterns around single *Tamarix* plant in the Hotan River Basin, Xinjiang (in Chinese). Arid Zone Res, 2006, 4: 539－543
22 Qong M, Takamura H, Hudaberdi M. Formation and internal structure of *Tamarix* cones in the Taklimakan Desert. J Arid Environ, 2002, 50: 81－97
23 Tengberg A. Nebkha dunes as indicators of wind erosion and land degradation in the Sahel zone of Burina Faso. J Arid Environ, 1995, 30: 265－282
24 Ling Y Q, Qu J J, Jin J. Influence of sparse natural vegetation on sand-transporting quantity (in Chinese). J Des Res, 2003, 1: 12－17
25 Langford R P. Nabkha (coppice dune) fields of south-central New Mexico, U. S. A. J Arid Environ, 2000, 46: 25－41
26 Nickling W G, Wolfe A S. The morphology and origin of nabkhas region of Mopti, Mali, West Africa. J Arid Environ, 1994, 28: 13－30
27 Yue X L, Ha S, Zhuang Y M, et al. Studies on sandy grassland nebkhas——A review (in Chinese). J Des Res, 2005, 5: 738－743
28 Liu Y H, Zhang C. A Study on the optimal model of sandbreak forest belt in Xiniiang (in Chinese). Arid Zone Res, 1992, 2: 13－26
29 Li S Y, Lei J Q, Xu X W, et al. Effects of the Tarim Desert Highway on the process of blown sand movement near the ground surface. Arid Zone Res, 2007, 2: 47－254